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Fog Shows Amazing Details over North Sea Wind Farm

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On 25 January 2016 at 12:45 UTC several photographs of the offshore wind farm Horns Rev 2 were taken by helicopter pilot Gitte Lundorff with an iPhone. A very shallow layer of fog covered the sea. The photos of the fog over the sea dramatically pictured the offshore wind farm wake. Researchers got together to investigate the atmospheric conditions at the time of the photos by analysing local meteorological observations and wind turbine information, satellite remote sensing and nearby radiosonde data. Two wake models and one mesoscale model were used to model the case and explain what was seen.

Figure 1. Photograph of the Horns Rev 2 Offshore Wind Farm on 25 January 2016 at 12:45 UTC seen from the south-southwest direction. Courtesy: Bel Air Aviation Denmark, Helicopter Services

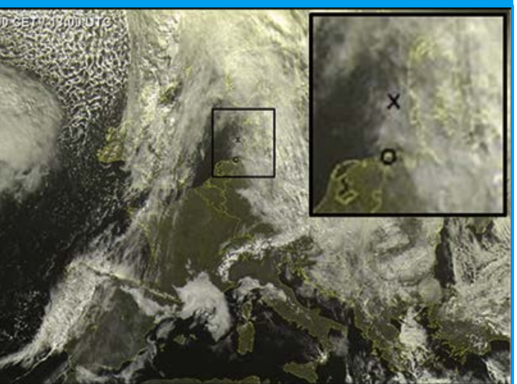

Figure 2. Cloud cover based on satellite data produced by ECMWF for Europe on 25 January 2016 at 13:00 UTC. The location of Horns Rev and Norderney are indicated by x and o respectively. Insert of zoom-in area. Courtesy: ECMWF

What the Photos Showed

The fog in the photos is cold-water advection fog that originates from warm humid air flowing from the southwest over cold sea. In the wake of the operating wind turbines the fog is lifted up by swirling motion. The fog extends downwind from each wind turbine. Interestingly the wakes are relatively long and narrow. Meteorological observations and satellite data show the atmosphere to be stably stratified and this corresponds well to modest wake expansion. Furthermore it is noticed that the fog disperses downwind of the wind farm. This process is explained by additional mixture of warmer, drier air aloft.

Motivation for the Research

Because the photos of fog over the sea stunningly visualised the offshore wind farm wake, five researchers from DTU Wind Energy and one senior wind energy analyst from DONG Energy got together to analyse and model the atmospheric conditions and processes of the eye-catching photos.

The research questions posed were:

- Do the fog trails correspond to the wakes?
- Why did the fog end?
- Do the visual wakes match the wind speed pattern?
- Does the wake model match the production pattern?

Horns Rev 2 Offshore Wind Farm

The Horns Rev 2 Offshore Wind Farm is located in the Danish North Sea. It covers approximately 35km2 and consists of 91 wind turbines and one transformer station. The transformer station is located east of the turbines and is visible as a white dot in the clearing of the fog (Figure 1). A service ship is also seen east of the wind farm. The turbines have rotor diameters of 93 metres and, with a hub height of 68 metres, the tip of the blades reaches from 21.5 to 114.5 metres above mean sea level. The distance between turbines is variable with a curved layout. The production was near the rated power of 2,300kW at the time of the photos.

Atmospheric Conditions

The shallow layer of undisturbed fog extends less than 20 metres above sea level (i.e. is below the lower tip of the blades). The wind speed was 13m/s and its direction 223 degrees at hub height. The sea surface temperature was around 5.2°C, while the air temperature at 26 metres was around 8.0°C. The ambient turbulence estimated from wind lidar data was around 3%. There was stable atmospheric stratification.

Satellite Data

Several Earth-observing satellites provided observations near the time of the photos. Cloud cover images from a mixture of geostationary and polar orbiting satellites show clear skies west of the wind farm and cloudy conditions east of it (Figure 2). A thin cloud layer at the site allows sunlight to light up the scene. The fog cones are sunlit at the southern part and in shade at the northern part.

Night-time sea surface temperatures retrieved from a mixture of thermal and passive microwave satellite data, gap filled and interpolated by the Danish Meteorological Office, show warmer surface water west of the wind farm up to 8°C and cooler water east of the wind farm down to 2°C (Figure 3). During windy, winter conditions sea surface temperatures are relatively constant during day and night, thus representative for the time of the photos. Scatterometer satellite data shows winds from the southwest in the region.

Wake Modelling by Two Approaches

The first approach used was the PARK model, a simple engineering model, with input of wind direction from the front row turbine nacelle anemometers and wind speed 13m/s. The results on wind power production from the SCADA data and model results compare well.

The other approach was to perform large eddy simulation (LES) for a single


Charlotte Hasager is a senior scientist at DTU Wind Energy with an MSc and PhD in Geography. She has undertaken research in offshore winds using satellite and ground-based remote sensing for wind profiles, wind power meteorology, wind resources and turbulence and has done experimental field work and theoretical work on atmospheric boundary layer structure and dynamics.


Patrick Volker, a post-doc at DTU Wind Energy, studied in his PhD the atmospheric impact of wind farm wake flows. He mainly works with mesoscale and microscale models to assess wind resources and to study the flow inside and around large wind farms.


Ioanna Karagali is a researcher at DTU Wind Energy who has a PhD in satellite remote sensing, an MSc in Coastal Engineering and a BSc in Oceanography. She works with satellite observations of ocean winds, sea surface temperature and significant wave height, ocean and atmospheric modelling and lidar measurements for wind field reconstruction.


Søren Juhl Andersen is assistant professor at DTU Wind Energy. A master in coastal engineering and a PhD in reduced order modeling of wakes in large wind farms. Research focus on numerical simulations of large wind farms. Previously, worked as coastal engineer for Water Technology, Melbourne, Australia.


Nicolai Gayle Nygaard is lead wind energy analyst at DONG Energy Wind Power. He holds a PhD in chemical physics. He works with wind resources assessment and wakes in offshore wind farms, focussing on modelling, data analysis and remote sensing.

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turbine wake with continuously seeding particles upwind of the rotor at two heights. The downwind movement and expansion of the wake is visualised from tracing the position of particles. Furthermore, an assumption that the particles behave as saturated/non-saturated at the dew point temperature is included. This gives estimates of the fog emergence and dispersion. The LES results compared with visual inspection of the fog in the photos thus gives indication of the fog development and pattern.

Mesoscale Modelling

Large-scale wind flow at the time of the photos was modelled by the Weather Research and Forecasting (WRF) mesoscale model. Further details as well as SCADA and meteorological data are given in Hasager et al. 2017 (Energies, 10, 317). The WRF model produces detailed results on the humidity, temperature and winds at several heights compared to nearby radiosonde data at Norderney.

The model has been run with and without a parametrisation for the wind farms in the Horns Rev area. Results from the two runs are subtracted (Figure 4). The differences in liquid water content at hub height between simulations with and without wind farms show a clearing of fog in the downwind area which extends for more than 100 kilometres. The tendency for dissolving of the fog layer at the end of and behind the wind farm in the photos is ascribed to admixture of warmer air from aloft. This process is caused by the wind farm wake

Summary

In summary the main conclusions related to the key questions are:

- Mixing associated with wakes can cause fog. The wakes are long and narrow due to the stable atmospheric stratification.
- The fog ends most likely due to downward mixing of warm, dry air from aloft. The process is caused by the wind farm wake.
- The fog is prevalent along the individual turbine wakes and builds up matching the wind speed pattern observed.
- The wind direction is critically important to reproduce the production of the wind farm correctly with the wake model.

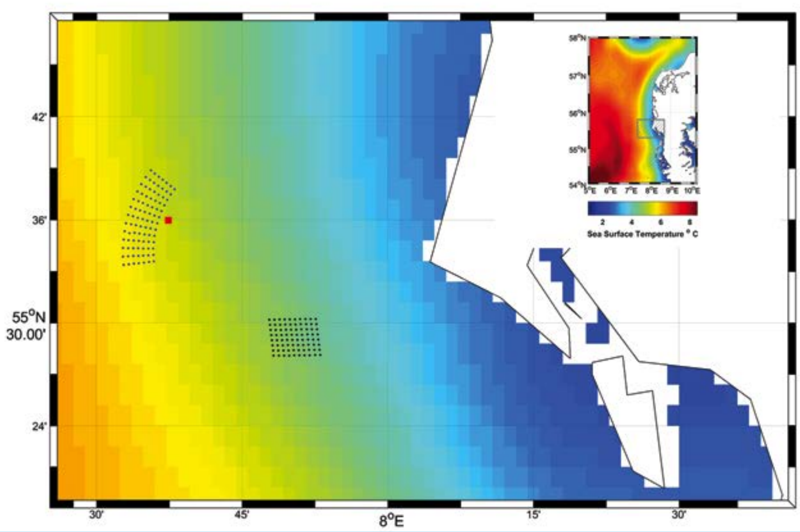

Figure 3. Map of sea surface temperature daily average for the western North Sea. The zoom-in area shows the location of offshore wind farms Horns Rev 1 and Horns Rev 2 on 25 January 2016. The red dot is the transformer station east of Horns Rev 2. The sea surface temperature map is courtesy of the Danish Meteorological Institute

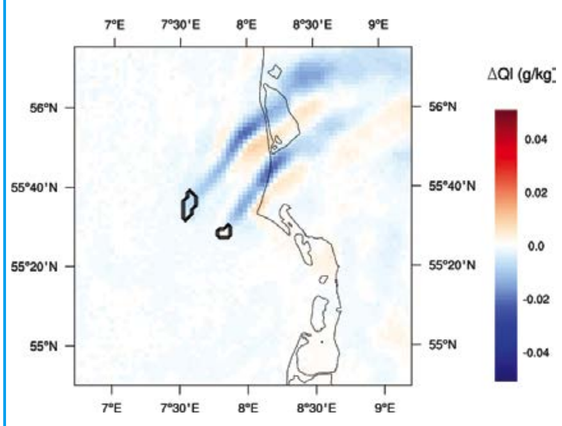

Figure 4. Map of the southwest North Sea based on WRF model results showing the difference in liquid water content at hub height between simulations with and without wind farms. The blue shading shows drier conditions downstream of the Horns Rev 1 and Horns Rev 2 wind farms